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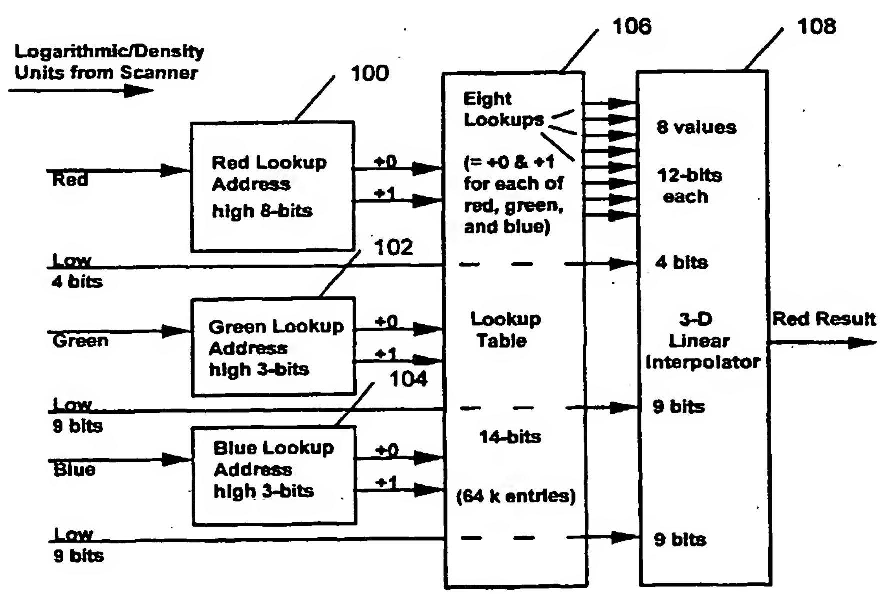

Red Cross-Color Correction System

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(57) Abstract: A color matching system, based upon a forward color match between transformed motion picture film images and electronic camera moving images, which operates in tandem with a corresponding inverted backward information ("inversion"). This forward and inversion pair of match transformations enables the matching of film and electronic images in both the film domain (by transforming the electronic image) as well as the electronic display domain (by transforming the film image).

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FILM AND VIDEO BI-DIRECTIONAL COLOR MATCHING SYSTEM AND METHOD

CROSS-REFERENCE TO RELATED APPLICATION

This application claims benefit of the priority of U.S. Provisional Application Serial No. 60/198,890, filed April 7, 2000 and entitled "Film and Video Bi-Directional Color Matching System and Method."

TECHNICAL FIELD

This invention relates to film and electronic video color matching systems.

BACKGROUND

Film Types and Characteristics. There are a wide variety of motion picture negative film types in common use. Some films have low contrast and wide dynamic range, while other films have high contrast and limited dynamic range. Also, there is a substantial variation in color saturation between film types. Some film negatives in common use reproduce colors fairly accurately. Other films increase saturation moderately, and yet other films increase saturation substantially. Some film negatives reduce color saturation (they "desaturate" the colors). Even a single film type will have variations due to the particular film emulsion chemical bath used at the time of manufacture, although effort is made to reduce this manufacturing variation. Print films and copy negative films each affect color saturation and contrast, as well as the quality of the blacks and whites.

A particular negative film will also behave differently depending upon its exposure. High exposure increases contrast and color saturation (when "printed down" onto a viewing print), but reduces detail and "headroom" range in the whites, bright areas, and highlights. Low exposure reduces contrast and saturation (when "printed up" onto a viewing print). Low exposure also increases the amount of grain noise in the middle exposures, as well as greatly increasing grain noise in the dark regions of the image.

There are some variations in developing processes (such as "flashing" which reduces contrast and raises blacks into the dark milky range). Such processes affect both color saturation and contrast.

In addition to the variations in the behaviors of films, photographing situations also vary widely. For example, on a hazy day, colors will be desaturated, blacks will be milky, and whites will lack sparkle (due to the diffuse sky reflection environment). However, on a sunny day with a high quality very clean lens, colors will be bright, blacks will be deep, and highlights will sparkle. Similar variations occur on set-based photography, although the widest ranges of uncontrollable variations occur with outdoor photography.

Digital Film Scanning and Printing. During the early 1970's, the use of motion picture films having a wide dynamic range of color and black-to-white tonal range generally was limited in motion pictures to experimental film work (or to the cumbersome three-strip Technicolor movie process). Most motion picture film (negative and print) at that time (*e.g.*, Eastman Kodak 5254) were limited in the range of color and black-to-white tones. Around 1976, Kodak Corporation introduced an improved negative film (Eastman Kodak 5247) having an extended color and black-to-white range, plus improved grain and resolution. These improvements in a color negative film made it feasible to consider developing improved methods of processing motion pictures.

Around 1976, one of the present inventors (Demos) developed a methodology for scanning color motion picture film by digitizing image information from a film negative using logarithmic density units. This methodology lead to the first color digital movie special effects involving high resolution digital image scanning, digital image processing, and digital image recording, for the "Samurai Warrior" sequence in the movie "Futureworld", released in 1976.

Further refinement of this color scanning technique lead to the development of a "Digital Film Printer" (DFP) system based upon precision Cathode Ray Tubes (CRTs) having a resolution in excess of 3000 vertical scanlines and horizontal pixels. The first DFP system scanned film and recorded 12-bit logarithmic numbers (having 11 bits of significance in the scanner, 12 bits in the film recorder). This degree of

resolution was based on the realization that films would eventually have higher quality than the negative color motion picture film available at that time.

For the highest accuracy in reproduction of color and black and white images, it has been necessary to provide for some correction of the color and black-to-white tonal ranges of both film and video images to provide proper printouts and/or electronic images on various imaging devices. A concept related to color correction is color matching, where colors from multiple sources are corrected to appear to have been derived from the same source. For example, photograph of movie shots from two different stages or sets may be intercut into a single scene. Other differences include different lights, lighting color drift, change of film stock or emulsions, or change of electronic cameras.

Around 1978, the DFP included a cross-color matrix correction technique for improving the color (including black-to-white range) adjustment and matching. Cross-color corrections allow arbitrary color adjustment for image quality and for matching of foreground and background colors.

In particular, a cross-color lookup table was designed to use the high order eight bits of the primary color, and the high order three bits of the two secondary colors to lookup cross-color correction. The bits below these high eight of the primary color, or three for each of the two secondary color influences, were linearly interpolated. Eight values (one unit above and below each target lookup value, in the primary and two secondary colors) were then used in the lookup, and linearly interpolated to obtain the final cross-color corrected result. This was done for each of red, green, and blue.

Such a lookup table method is somewhat more general than a matrix-based cross-color correction approach, since the amount of cross-color adjustment can be sensitive to brightness of each of the one primary and two secondary colors, and thus can vary over the entire range of hue and brightness. A matrix cross-color correction represents only a single cross-color term for the second two colors, equivalent to using only a single value for each. Having three bits, or eight values, effectively divides up the cross-color correction into eight ranges for each of the second two color influences, or 64 sectors of hue and brightness for each of 256 range values for

each of the primary red, green, and blue colors. The final eight-element three dimensional linear interpolation ensures smooth piece-wise linear correction for the remaining bits. In the various DFP embodiments in the 1970s, the pixels were represented by 12-bits of logarithmic/density units, so the precision of the eight and three bit lookups was extended by four and nine bits, respectively, during the linear interpolation.

FIG. 1 is a diagram showing one channel (red, in this instance) of such a prior art cross-color correction system, the function of which is to correct a primary color as a function of its own value and the values of the other two primary colors. The 8 high order bits of red channel address data are applied to a lookup table 100, while the 3 high order bits from the green and blue channels are applied to similar lookup tables 102, 104. The symbols "+0" in the diagram indicate the lookup table value corresponding to the truncated high order (8-bit or 3-bit) bits of the input address value. The symbol "+1" indicates the lookup table value corresponding to one above this truncated value. These two values (the lookup corresponding to the truncated address and one above it) then form the two end points for linear interpolation. The initial lookup values from tables 100, 102, and 104 are then applied to a lookup table 106, which outputs 8 bits to a 3-D linear interpolator 108. The 3-D linear interpolator 108 applies the low order 4 bits, 9 bits, and 9 bits for red, green, and blue, respectively, to interpolate between the eight 12-bit lookup values.

The green and blue channels have the same structure, except that for green, the 8-bit lookup is for the green input, and for blue the 8-bit lookup is for the blue input. Thus, the diagram is nearly identical except that the top channel becomes green for the green output, and blue for the blue output (with red moving to the appropriate bottom 3-bit lookup channel).

Known improvements to the cross-color correction system include interactive control by a user. For example, a digital slider system (*e.g.*, having 12 sliders in 1978), has been used to provide interactive control of color adjustment parameters of the a cross-color lookup system.

Logarithm Density Units. One approach developed by one of the present inventors (Demos) to provide the best density range calibration for scanning negative

film was to look for the widest range of minimum and maximum density on the variety of negative orange-mask films that might be useful to scan. This implies that in normal practice any particular negative will not span the entire range of available density measurement. It also implies that a minimum density for each negative would be a variation which should be removed with every negative type scanned. The minimum density of color negative film varies randomly, and is an artifact of film emulsion manufacture and developing, and therefore does not represent any image information. Above this minimum density, all density values represent actual image brightness and color variation. Also, exposure and color balance adjustments are naturally applied. These logarithmic density color measurements, less the minimum density, could then be used to expose new color negative film, after color balancing, to perform digital effects processing.

The goal of this prior work was to match computer generated images with images scanned digitally (in logarithmic density units) from film, and to match multiple different film images with each other (each being photographed under different lighting conditions).

Scanner and Printers. Around 1991, Kodak Corporation introduced new "T-Grain" film negative stocks (5245 and 5248), which again improved the dynamic range and fineness of grain compared to prior film stock. About this time, a number of companies introduced color image scanning systems based upon CCDs (Charge Coupled Devices) instead of CRTs. These introductions were following by the introduction by a number of companies of laser film recording systems. An advantage of a laser film recorder is that slower-speed finer grain and higher resolution (so called "intermediate") negative films can be used for film recording, providing increased quality and wider image brightness range on the recorded film. Presently, essentially all modern CCD scanners and laser recorders use logarithmic density units for film scanning and recording.

CRT Display Technology. Most color viewing on computer workstations is still based on cathode ray tube (CRT) technology. While micro-mirror projectors, plasma and active-matrix LCD flat panels are being introduced, most precision color work still uses CRTs. This is somewhat odd, since CRTs are notorious for both drift

and unevenness. Moreover, a CRT is usually set to respond to digital pixel brightness and color RGB values through an exponentiated value representation. This differs from logarithmic density units in various known ways. Further, a CRT uses color primaries for red, green, and blue, which are limited to available phosphors. These primaries differ from the color primaries which result from motion picture film print dyes.

Electronic Cameras. Electronic moving image cameras have been continuously improving since the first days of television. In recent years the first high resolution (also called "high definition") video cameras have been developed which use progressive scanning rather than interlaced scanning. Interlace creates numerous artifacts which detract from the quality of the image. The first such color high definition progressive scan camera was first demonstrated in 1997.

Based on the advances in film stock, scanning and printing technology, display and camera technology, and computer processing power, the inventors have determined that it would be useful to have an improved method and system of color correction and matching. The present invention provides such a method and system, much of which is suitable for computer implementation.

SUMMARY

It is a highly desirable goal to be able to bi-directionally match electronic camera images and film images in terms of color, brightness ranges, and tone characteristics. This enables electronic cameras to be used to make film, and enables film to be used to make electronic images, such that both media can be mixed and matched. This invention provides a practical system for consistently achieving this goal.

In particular, the invention encompasses a color matching system, based upon a forward color match between transformed motion picture film images and electronic camera moving images, which operates in tandem with a corresponding inverted backward transformation ("inversion"). This forward and inversion pair of match transformations enables the matching of film and electronic images in both the film domain (by transforming the electronic image) as well as the electronic display domain (by transforming the film image).

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

FIG. 1 is a diagram showing one channel of a prior art cross-color correction system, the function of which is to correct a primary color as a function of its own value and the values of the other two primary colors.

FIG. 2 is a flowchart of a film scanning and matching process using the forward correction steps of the preferred embodiment of the invention.

FIG. 3 is a flowchart showing the preferred steps for performing an inverted correction for electronic images for recording onto film in accordance with one embodiment of the invention.

FIG. 4 is a diagram of cross-color adjustment space selection pathways.

FIG. 5 shows a diagram of a typical highlight response of incoming light intensity vs. camera output, depicting the breakpoint for the knee.

FIG. 6 is a graph of the results of a typical black stretch remapping.

FIG. 7 is a diagram of a typical calibration setup for an electronic camera.

FIG. 8A shows a graph of typical color sensing curves for red, green, and blue primary colors.

FIG. 8B shows a graph of possible color sensing curves using red, green, blue, and four additional "primary" colors.

FIG. 9 is a color space chart with a conventional RGB gamut, and the boundary points of an extended gamut that could be provided by adding violet, cyan, deep green, yellow, and deep red primary colors.

FIG. 10 is a block diagram of a cross-color correction system for use with more than three primary colors.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

Overview

It is a highly desirable goal to be able to bi-directionally match electronic camera images and film images in terms of color, brightness ranges, and tone characteristics. This enables electronic cameras to be used to make film, and enables film to be used to make electronic images, such that both media can be mixed and matched. This invention provides a practical system for consistently achieving this goal.

In order to achieve a match, it is most desirable to have both a "forward" match from film logarithmic density units to an electronic image display device (*e.g.*, a CRT display), as well as a "backward" match from an electronic image into film logarithmic density units. The concept of "forward" and "backward" allows an electronic imaging device to be used to interactively match an electronic image with a scanned film image by only adjusting the scanned film image using logarithmic density data. This is practically useful, considering that the electronic image is monitored while being photographed, and thereby interactively adjusted to be approximately correct for final use. A negative film image, however, is generally adjusted via color correction when making a print for viewing. Thus, the normal use of film negative is to adjust for print viewing, whereas the normal use of an electronic image is to be nearly correctly adjusted during the photography.

Forward Correction

Forward correction of image data from digitally scanned film to match an electronic display requires a conversion from logarithmic density units to electronic display units. In the preferred embodiment, forward correction also removes (via subtraction) the minimum density value, and adjusts color and exposure characteristics (as is used to print from the negative).

In addition, color saturation differences and primary color differences between film and electronic displays, plus film cross-color affects, need to be modeled. These characteristics can be modeled via use of a matrix for color transformation.

Alternatively, they can be modeled by converting to a hue-saturation-value (HSV) system, the CIE LUV system, or any other similar color space wherein saturation and hue can be adjusted. As an additional enhancement, it is useful to also model the "S" curve of a film negative's and print's "toe" black region and "shoulder" white highlight region.

FIG. 2 is a flowchart of a film scanning and matching process using the forward correction steps of the preferred embodiment of the invention:

STEP 200: Digitally scan a film into pixel values expressed in logarithmic density units.

STEP 202: Optionally, store the scanned pixel data values.

STEP 204: Prior to color matching, remove the minimum film density level from all pixels (*e.g.*, by subtracting the minimum film density value from all pixels).

STEP 206: Color matching: apply a cross-color matrix (or, alternatively, a lookup table) adjustment to all pixel values.

STEP 208: Color matching: make any desired fine color adjustments manually (such as the color range of each of red, green, and blue on the negative, and fine color and exposure balance adjustments).

STEP 210: Color matching: adjust the highlights and very light and bright areas.

STEP 212: Color matching: convert the adjusted pixel data values to an electronic display space (*e.g.*, CRT display values) by mapping via a lookup table or algorithmic transformation.

STEP 214: View the converted pixel data on an electronic viewing device (*e.g.*, a CRT).

The Inversion Process

In order to transform electronic images to logarithmic density units for recording onto film, the above forward correction is essentially inverted. That is, the

conversion lookup tables (STEP 212) are used in a backward manner, and the matrix for cross-color correction (STEP 206) is inverted.

FIG. 3 is a flowchart showing the preferred steps for performing (among other things) an inverted correction for electronic images for recording onto film.

STEP 300: Digitally scan a film into pixel values expressed in logarithmic density units.

STEP 302: Forward match (*i.e.*, color correct and convert as shown in FIG. 2) the pixel values to the electronic display space of a selected electronic viewing device.

STEP 304: Display the forward matched pixels on the selected electronic viewing device. Optionally, a viewer may adjust the match manually while viewing the display.

STEP 306: Display the output of an electronic camera on the selected electronic viewing device for side-by-side or sequential viewing with the forward matched pixels from the film scanning/converting process.

STEP 308: Obtain the conversion parameters (*e.g.*, S-curve parameters, cross-color correction matrix or lookup tables, conversion lookup tables, *etc.*) from the forward match from FIG. 2.

STEP 310: Invert the conversion parameters (*e.g.*, by reversing the conversion lookup tables (STEP 212), inverting the matrix (or lookup tables) for cross-color correction (STEP 206), *etc.*), thus enabling reversal of most of the forward correction steps (*i.e.*, STEPS 206, 208, 210, 212).

STEP 312: Apply the inverted conversion parameters to the output of the electronic camera to generate logarithmic density units that are matched to the original scanned film (*i.e.*, essentially the forward color matching process run backwards, but excluding STEP 204, removal of the minimum film density).

STEP 314: Apply the generated logarithmic density units from the electronic camera to a film recorder to produce a new film that is matched to the original scanned film.

Cross-Color Correction

In motion picture film negative, the color sensing layers for red, green, and blue, interact. These interactions introduce dependencies between the colors. Thus, the amount of red depends upon the amount of green and/or blue. Similarly, green is somewhat dependent on the amounts of red and blue, and blue is somewhat dependent on the amounts of red and green.

This can be seen in practice with a gray wedge (gradation) chart, together with color charts. The gray wedge may be correctly balanced, but the color may be over or under saturated. Further, colors which use more than one primary (of red, green, or blue) such as yellow, cyan, magenta, and flesh tones, may have incorrect hues. For example, yellow may be either more red or more green than it should be. Flesh tones may contain too much red or green.

These effects can all be completely corrected using a cross-color matrix, in known fashion. A cross-color matrix simply corrects the amount of red based upon the amount of green and/or blue. Similarly it corrects green (from red and/or blue) and blue (from red and/or green).

Color Spaces For Cross-Color Correction

Color corrections can also be performed by adjustments applied in alternate color spaces, such as a hue-saturation-value space. In such spaces, color saturation can be adjusted directly overall, as well as by a function of hue. Thus, for example, yellow hues can be either increased or decreased in their saturation. Further, hues in a particular region can be adjusted. Thus, yellow hues can be adjusted either toward red, or toward green, as appropriate.

With film, the amount of cross-color affect may be a function of the exposure level, or it may be a relatively constant amount of affect at any particular exposure.

This distinction affects the adjustment of dark areas (*e.g.*, dark yellow in shadows) vs. light areas (*e.g.*, light yellow in bright scene areas).

A matrix adjustment is a linear operator. If applied to the light energy in the linear space, the matrix will correct the hues independently of the exposure level. However, some cross-color affects are a function of exposure. For such affects, the matrix can be applied to a non-linear representation of exposure, such as logarithmic density units, or other appropriate non-linear representation.

FIG. 4 is a diagram of cross-color adjustment space selection pathways, showing a number of possible color matching procedures. A film is scanned to generate logarithmic density units (STEP 400). A decision is made to not convert to another color space (STEP 402, to perform a linear color space conversion (STEP 404), or to perform some other type of color space conversion (STEP 406). Then a color transformation is performed by means, for example, of a matrix transformation (STEP 408), or by applying a transformation based on adjusting alternative color space parameters (STEP 410). If a color space conversion was performed (STEPS 404 or 406), the inverse color space conversion may be performed if a return to the original color space is desired or required (STEP 412). Additional color processing may be performed as needed (STEP 414).

Color Ranges for Cross-Color Conversion

In addition to benefiting from different colors spaces when applying a matrix cross-color correction, it is also often useful to apply different amounts of cross-color correction for different image brightness and color ranges.

As described above, the original DFP cross-color conversion system utilized 8-bits of lookup for the primary color, and 3-bits of lookup for each of the two secondary colors. The low order bits were then linearly interpolated. The 3-bits of secondary cross-color adjustment amount effectively segmented the secondary cross color value into 8 ranges for each of the two secondary colors, or 64 ranges when considering both secondary colors. These 8 and 64 ranges were provided for each of 256 ranges of brightness in the primary color being corrected.

The limitations of developing a high speed hardware lookup and interpolation system in 1980 were central to the selection of 8 and 3 bits for the table lookups. Using current electronic and/or computer technology, a cross-color general lookup system can utilize many more than 8 bits of primary color lookup, and many more than 3 bits of each secondary color lookup (with correspondingly fewer bits of linear interpolation required). This structure is effective over a wide range of cross color lookup memory sizes. The useful range extends from far below 8, 3, and 3, bits, up to far more. Using such a technique, cross-color correction can be applied in a much more general way than is possible with a single matrix operator.

As a subset of this generality, it is possible to build lookup tables by conceptually describing a cross-color conversion matrix for each color range. Thus, for bright oranges, one matrix might be used, whereas for dark oranges, a different matrix might be used. Thus, the amount of color saturation and hue shift required in the orange of the scene can be controlled based upon the brightness or shadow of the orange object. The range can be further divided, for example, into very dark orange, dark orange, medium dark orange, medium orange, medium bright orange, bright orange, and very bright orange.

In this way, the simplicity of the matrix technique can be combined with the generality of a cross-color lookup system. In practice, a single cross-color matrix in an appropriate brightness unit space can usually provide the cross-corrections needed. However, it is sometimes desirable to divide the amount of cross-color correction into brightness ranges, such as dark, medium, and bright, so that adjustments in the shadow, medium, and bright regions can be independently controlled.

For simple multi-matrix cross color correction structures, a straightforward multi-matrix inversion can be utilized. For complex cross-color structures, an inverse lookup system can be utilized. Such an inverse lookup system can have the same lookup structure as the forward cross-color lookup system. The entries in the forward lookup tables may be created using any desired mapping technique (*e.g.*, using a multi-matrix cross-color correction). A simple method of creating a fully general inverse set of tables is to create the inverse table at the same time as the creation of the forward table, by using the values for addresses, and the addresses for values. For

the values not touched, a record must be kept (*e.g.*, via a binary touch buffer), and an interpolated value fill step must be performed to complete the inverse table. Thus, the color inversion method of this invention is completely general.

Modeling the S-Curve

For purposes of matching electronic movie camera images with film movie camera images, the highlight and shadow treatments will often need to be adjusted.

In electronic cameras, the highlight response will often have a "knee" function, with a knee breakpoint and knee slope. FIG. 5 shows a diagram of a typical highlight response of incoming light intensity vs. camera output, depicting the breakpoint for the knee.

This knee function corresponds to the well-known "shoulder" (S-curve) behavior of film. The shoulder behavior of film is the concatenation of the film negative's shoulder and the print film's shoulder. Negative film has a much wider dynamic range than print film, so the print film's shoulder often dominates, unless the negative is near to overexposure.

The shoulder for film differs from the electronic knee function in that the "S" curve of the film shoulder is more "rounded". However, the electronic camera knee function can reasonably approximate the behavior of the shoulder for film.

For matching purposes, this shoulder behavior must be taken into account. In order to handle this, the preferred embodiment of the invention utilizes an amount and an exponent in the forward correction. This shoulder technique for simulating a print from film exponentiates the values approaching full exposure, and weights this exponentiated value based upon the amount specified. A typical shoulder can be simulated by using a weighting amount of 0.3 and an exponent of 4.0. The useful range of amount is 0.05 to 0.8, and the useful range of the exponent is 0.7 to 8.0.

For the "toe" black region of negative and print film, there are similar issues. The negative film's low exposures become significant since they often are near underexposure, and such regions become both grainy and desaturated in color (sometimes called "muddy"). The black region on the print is usually less important for a fully exposed negative, since the black portion of a print receives the most light,

and is therefore fully exposed. However, print film exhibits some black region affects if the negative is underexposed, since the print is then also underexposed, resulting in a weak ("muddy") black on the print.

In electronic cameras, the toe affect can be simulated by using the "black stretch" technique to electronically re-map the shadow response by extending the region of black exposure up into higher ranges of output. FIG. 6 is a graph of the results of a typical black stretch remapping.

Just as with film grain on the negative, electronic camera noise is also increased when using black stretch. For this reason, black stretch is often deemed undesirable, unless there is a strong need for increasing the visibility of shadow details.

Negative vs. Print

Since the film negative is scanned for conversion to an electronic image, there is generally no film print involved in the color matching process described above. However, a scanned image may be re-recorded onto new negative film which then will be printed for film-based viewing. Thus, it is often necessary to "simulate" the film print for viewing and matching purposes. The forward process described above allows a thorough simulation of the film print image. It also includes a conversion to electronic display units for viewing on an electronic device.

Thus, the scanned film negative image, from its native logarithmic density units, is matched using the forward correction described above. While the print is simulated for viewing, the use of an inversion of this process "nulls out" the affects of the print film which will be used to print the new exposed negative. Thus, the new negative will contain the proper information to expose print film to create a correctly matched and color adjusted image.

Since an electronic camera provides "black stretch" and a "knee function", the electronic camera is already simulating the behavior of concatenating film negative and film print for viewing.

Electronic Display Space

While color CRTs are the dominant color viewing reference device, an inferior range of color primaries and inherent drift make the CRT somewhat undesirable as an accurate reference quality imaging device for viewing digitized film. Recently, alternative technologies have been developed which are both more stable as well as having wider color gamut via better color primaries. Such technologies include active matrix direct view flat panel displays.

One of the most interesting new technologies for imaging displays is the Texas Instruments Corporation "micromirror" chip. Current versions of this chip use around 10^6 tiny mirrors which are modulated to reflect light in an "on" or "off" state at rates on the order of 100 kHz. Using this digital binary time modulation, a very stable light reflector is obtained. When using an equally stable light source, the micromirror chip can produce an image with sufficient stability to use for color reference. The projected image can be as bright as motion picture film projectors, and can have a dynamic (black to white) range comparable to projected film prints (in excess of 500:1). Further, the color prism assembly can be made with wide color gamut color primaries which are "film-like".

A key feature to consider when optimizing a digital brightness representation for a micromirror projector is that the values modulating the mirrors become ineffective near the limit of light extinction when representing "black". This phenomenon is also true for CRTs, due to room scattered light hitting the screen, and for motion picture film, where grain noise and maximum print density (minimum negative density) dominate the black light level compared to any signal.

The preferred embodiment uses logarithmic light units for representing the dynamic range of an electronic imaging devices. This approach allows a simple numerical correspondence between digital brightness values and light on a display (or projection) screen. However, a wide variety of alternative digital representations, most of them with roots in analog NTSC and PAL television systems (and recently, HDTV), dominate the so-called "gamma" representation used for CRT viewing. The 2.2 "gamma" with black correction, which is now standardized with small variations for HDTV, NTSC, and PAL digital television systems, is optimized for a 250:1

dynamic black-to-white range. For wider dynamic ranges, alternative representations are more optimal.

In a logarithmic representation, given 10, 12, or more bits, the range of the logarithmic values can be set, together with a percentage digital step size, to represent any particular dynamic range. Alternative representations include "higher gamma" and other wider range treatments.

At present, given the lack of useful standardization for wide-dynamic-range viewing, it is most practical to support all of the representations which may occur for driving electronic displays.

All of these representations, including the pure logarithmic, differ from the logarithmic density units used to scan film. At a minimum, the superfluous minimum density of negative film should always be removed, usually simultaneously providing an overall color correction (similar to "printer points" when printing from negative film).

Thus, the only certainty of electronic displays is that there will be some degree of difference from film digital scanning units, and that there are likely to be at least several digital representations for display.

The present invention allows for a choice of calibrated electronic representation and display, but is not dependent upon any particular calibration.

Display While Capturing Electronically

Electronic cameras are operated by a combination of gray-chart calibration and manual image-viewing-based adjustment. FIG. 7 is a diagram of a typical calibration setup for an electronic camera 700. The gray-chart calibration portion of the setup is usually performed using a reference chart 702 of black, a white, and one or more mid-gray tones illuminated by desired scene lighting 704. A waveform monitor 706 is used to set the black-to-white range, and white levels for the red, green and blue sensors of the camera 700. The mid-gray gamma and balance are adjusted once the black and white levels are set. The precision provided by the waveform monitor 706 is typically a few percent, which is sufficient for making sure the image is within range, but does not represent a finely accurate calibration. A gray-chart

calibration finer than this few percent is usually not performed while using electronic cameras in practice. Fine adjustments generally are performed after the fact (during "post production").

Image-viewing-based adjustments generally are performed manually while viewing a color reference monitor. The black, white, gray gamma, and color balance are often adjusted based upon the image seen on a reference color monitor. However, it is usually the case that the "reference" color monitor is not itself calibrated. In practice, the viewing environment (light spill, color temperature of the surrounding viewing area, *etc.*) is also usually not calibrated. Thus, there are factors which hinder the accuracy of judgment based upon viewing the reference monitor.

In the preferred embodiment, the quality of the adjustments which are made based upon viewing a reference color monitor are optimized by the following steps:

1) Ensure that the monitor itself is close to an accurate reference calibration. That is, that the primary colors are known, and the black and white levels are set properly. Also ensure that the gamma (gray tone) curve corresponds to a known relationship between the digital pixel values and the brightness emitted from the display.

2) Control the viewing environment using a gray surround material having a known color temperature (such as the 3600K, 5400K, or D65 standards), with a fairly low light level (*e.g.*, within a booth). Also, minimize the amount of external "spill" light (especially colored light or daylight) which falls upon the viewing screen. For example, an enclosed "on-set" small viewing area, with a micromirror projector, provides a closer viewing match to that of film than will a 20-inch color CRT positioned near the camera. However, practical limitations will often dictate the use of such a CRT. When using a CRT, attempt to put it into a dim alcove or recessed into a mobile kiosk with a gray cloth surround of proper color temperature, if possible.

3) The eyepiece or camera-top viewfinder should be black-and-white, and should not be used for color or black-white or gamma calibration. It should only be used for framing. The viewfinders available presently are of insufficient quality and the viewing conditions make them unsuitable for reference adjustments.

4) Effects of lighting should be considered with respect to the electronic adjustments. For example, electronic cameras can easily compensate for daylight vs. tungsten lighting. Thus, overall color balance is not problematic to adjust solely with electronic controls (usually by varying the blue sensitivity). However, the amount of light in the shadows may be best adjusted by adding lighting, since electronically increasing sensitivity to dark areas will increase the noise present in those areas. Similarly, contrast range should be established with proper lighting, and not primarily with electronic contrast adjustments. The "knee" function for highlights is limited in capability on electronic cameras and may decrease saturation in bright areas of the scene. Thus, it is often best to tone-down bright highlight areas with lighting, rather than attempting to prevent them from "white clipping" using the knee function. The knee function should only be used heavily if highlights cannot otherwise be controlled with lighting techniques. A small amount of knee use, however, will often be desirable as an improvement to the appearance of highlights as an augmentation to the final lighting adjustments.

Reference monitor viewing condition optimization issues should be carefully considered when using an electronic camera. The consistency and quality of the output electronic images is substantially dependent upon the quality of the image-viewing-based calibration.

Gray-chart calibration ensures that the image was captured in such a way as not to be out of range in black or white, and not to deviate from a useable gamma for mid-gray values. When viewing conditions for the color image monitoring are poor (which is common in practice, especially on location), the gray-chart calibration should be relied upon most heavily.

Lighting must use some form of reference monitor to judge the results. Thus, gray-chart calibration is mainly useful in situations where lighting is otherwise uncontrolled or not very controllable, such as outdoors. On-set lighting quality will be dependent upon the skill of the director of photography ("cinematographer") based upon experience, combined with the quality of the viewing reference monitor used, by which the cinematographer will be judging the quality of each particular lighting setup.

Film Match For Electronic Capture

Another aspect of the invention is the use of a still camera, containing motion picture film negative, to photograph each shot from near to the same location and view as an electronic camera. In this way, a contemporaneous motion picture film negative of the same scene lighting conditions is actually obtained for matching with electronic camera images. The still film negative can then be scanned using logarithmic density units, which can be used as described above for matching the film to an electronic color reference display device.

Once a match is obtained using the still film images, the inversion process described above can then be used to transform the electronic images into the same logarithmic density values as the film negative. These logarithmic density values can then be used with a film recorder to create a film-based matching copy of each electronically captured shot. When done for all shots in a movie, a film-based release is created for the entire electronic movie.

It is easily understood that the same scenes, photographed on that particular negative film, and then printed for film theatrical release, would then be virtually identical to the electronic image with the invention matching conversion applied. Many films are scanned and film recorded in order to apply digital effects, composites, or various other adjustments. In such a case, the step of re-recording the scanned negative onto film forms a virtual equivalent to film recording the electronic image which has been converted through the inventive forward-matching backward-inversion process.

A film-based release becomes economically crucial, since film-based release is the way in which movies earn their initial income. Electronic projection equipped theaters can also show the electronic version of the movie. Initially, very few movie theaters (at present only a handful) will have electronic projectors. However, with time, it is anticipated that the entire movie exhibition industry will gradually convert to digital projection.

Similarly, no high quality movies have yet been made with electronic cameras. However, it is anticipated that, using this invention, electronic cameras can be used to make entire high quality movies, which can then be released both electronically as

well as on film. Further, since this invention provides for a full match between film and electronic camera images, portions of a film can be photographed on film, and other portions can be photographed with electronic cameras, yet both portions can be made to match.

This aspect of the invention can be used to match a heterogeneous variety of motion picture film types and photographing conditions, as well as to match a variety of different electronic cameras, which may have different settings on each camera on each shot, and which cameras may differ from each other in color primaries and other fundamental sensing characteristics.

Generic Match Calibration

It is useful to build a database library of match calibrations for a variety of film stocks and electronic camera types photographing under various lighting and scene-content conditions. These "generic" matches are useful in providing initial matching calibrations, where fine adjustments can then be applied. The generic matches are also useful as a primary reference for matching when no film-based comparison image is available.

Using generic matches, some additional adjustment will usually be desirable. For this purpose, the invention can be used to invert the electronic image using the generic match's inversion parameters, and then re-forward adjust (match) the result using the electronic display as a reference. By applying new further adjustments in this forward adjustment mode, an image with the desired color, brightness range, and tone characteristics can result.

Since no actual photography using a particular film may have occurred together with the electronic photography, generic calibration relies on a calibration chart in order to set up the generic inversion. The logarithmic density behavior of a particular negative film when viewing a particular test chart can be specified in the generic library. For these purposes, it is most useful to include color patches (such as the well-known "MacBeth" color chart) in addition to gray wedges, since color saturation must also be processed in addition to overall exposure.

Once a test chart is viewed using the electronic camera, a human-assisted matching process (using an electronic display) or an automated matching process (by algorithmically iterating adjustments until a match is found) can be performed using this invention. This is preferably accomplished by first forward adjusting the generic color chart in the database until it matches the electronic image, and then applying the inversion process. Using this information, the actual scene can be photographed electronically. Then, using a specific inversion (as determined by a color chart match), and then applying the generic forward transformation, the electronic view of a logarithmic density scan of the particular generic film type can simulated. The result is as if that film type had been used to photograph the real scene, and then had been scanned and viewed electronically, even though the image is actually being photographed electronically.

Further, a film negative and print can then be made, such that the image on film will appear nearly the same as if the original scene had been photographed using a specific type of film. Note that a different film can be used for film recording than the film being simulated, since the densities produced on the negative are numeric, and are thus controlled by the film-recorder's calibration for its specific recording film. This will be an intermediate film in the case of a laser recorder. This process is most similar to having scanned the particular film type being simulated, as if it had been used to photograph the scene, and then re-recording that logarithmic density data back out onto film.

Once the behavior of a particular film is established, it is usually desirable to perform additional adjustments. The adjustments can be made to the simulated film's behavior. For example, "printing lights" can be simulated to adjust the image as if it were on a film negative. Then the generic inversion and the new adjusted inversion can be combined to create a full inversion for application to the electronic image. As an alternative, the electronic images can be adjusted directly, with that adjustment then being applied as step prior to the generic inversion.

Sometimes no calibration chart can be conveniently utilized that would capture the exposure characteristics of a particular scene (such as very long telephoto photography outdoors). In the absence of a color chart, various generic matching

conversion-inversion sets can be examined in order to get close to a film's behavior for the same electronic image. In these cases of no calibration chart, the "open loop" nature of the film matching side of this process precludes a complete match. However, experience with the generic calibration database can yield selections of generic match film calibrations which are close to a test-chart-based calibrated match, and therefore form useful film conversion selections for the electronic image.

An uncalibrated *situation* exists when using these techniques to achieve fine adjustments, or when no test chart is available for matching (against the generic film-based-chart database). These situations will sometimes require a film-recorded check print to be made in order to make final film color adjustments, since no reference matching film exists. However, the techniques in this invention will result in the film print being close to the desired result, so that such further film-based iteration adjustments will consist of small changes. Also, the use of the generic film matching process, using a properly exposed test chart, will usually achieve an accurate simulation of any film stock and exposure and printing configuration in the generic database described above.

Gamut

The color "gamut" is the range of colors available from a particular set of color primaries. All film and television systems are currently based upon three color primaries, being red, green, and blue. The human eye is sensitive to combinations of these colors, and can build other colors such as yellow, orange, magenta, cyan, brown, *etc.*, from these three primaries. However, the range of colors is limited by the color purity of the particular red, green, and blue which is used. NTSC television, and even many proposed HDTV systems, use very limited color primaries due to historic limitations in CRT phosphor availability. Also, variations in the exact color of a particular primary will cause errors in the reproduction of colors.

With new CCD camera sensing technologies, and with new display technologies such as micro-mirror displays and flat-panel active-matrix LCDs, it is possible to use purer color primaries. A natural improvement is to move the color primaries closer to the purest color primaries available from film-based dye systems.

Recent demonstrations have shown that substantial improvements result from improving the purity of red, green, and blue primaries.

In addition to improving red, green, and blue primaries, it is also possible to conceive of systems which extend the range of colors by using additional primaries. This technique has been used in the subtractive-color world of paper ink color printing. By adding additional ink colors (*e.g.*, green or orange) to the yellow, cyan, and magenta subtractive primaries (which are the blue, red, and green modulators, respectively), the relatively narrow gamut of these inks can be increased. In addition to improving black by using black ink, additional color primaries are also added in the highest quality printing.

In electronic cameras and displays, however, the range of color has been relatively satisfactory using red, green, and blue primaries, especially when pure colors are used. FIG. 8A shows a graph of typical color sensing curves for red, green, and blue primary colors. However, the possibility to extend this range does exist. The use of additional sensor primaries in electronic cameras, and display primaries in electronic display systems involves additional cost and effort. Up until the present, this additional cost has not justified much exploration of extra primaries, and certainly there are no commercially available electronic cameras or displays with more than three primaries. However, it is anticipated that with quality improvements to the rest of the electronic camera and display systems, the potential of extended color range will also become feasible and desirable. FIG. 8B shows a graph of possible color sensing curves using red, green, blue, and four additional "primary" colors. FIG. 9 is a color space chart with a conventional RGB gamut 900, and the boundary points of an extended gamut that could be provided by adding violet, cyan, deep green, yellow, and deep red primary colors.

There is also additional benefit in color matching between electronic systems, since the additional information and range provided by using additional primaries can improve color matches.

As mentioned above, red, green, and blue primary systems can have mismatched colors when different systems use significantly different color primaries. Much of this can be corrected by the cross-color corrections described above.

However, additional matching improvements are possible with additional information. Thus, additional primaries can aid in color matching, even when matching with a three-color-primary system.

Of additional potential is the possibility of retaining a match with existing three-color-primary systems, while providing a framework for adding new color primaries for those systems so-equipped.

The cross-color correction systems described above can be extended to four, five, six, seven or more primary inputs and outputs. In addition, multiple cross-color correction systems can be used for each color primary system, providing simultaneous corrected colors and color matching for multiple variations in color primaries. For example, FIG. 10 is a block diagram of a cross-color correction system for use with more than three primary colors. Each primary color 1...*n* is input to a cross-color correction system 1000-1...1000-*n* comprising a system similar to that shown in FIG. 1. For every primary color *n*, and transformed new primary *n'* is output.

In the cases of extending the gamut by using purer red, green, and blue, or by using additional primaries, there will be regions of color which cannot be converted. This is referred to as "out of gamut" color. If there is a wider gamut of the incoming colors (such as from a new wide-gamut electronic camera, perhaps with more than three primaries), the output gamut can utilize the full range available for the transformed colors. The out-of-gamut issue arises when the incoming color range exceeds the range of the display device (or film) to which we are transforming.

Various techniques can be utilized for handling the out-of-gamut situation. The most widely used technique is to "clip" to the range of the outgoing (more limited) gamut. However, any variations in saturation beyond the output range are then lost. Another known technique is to apply the same concept as the shoulder of the "S-curve" to compress the gamut values, thereby bringing the saturated gamut in range while maintaining some differentiation. Either of these techniques, or their combination, can utilize the cross-color correction system to achieve the desired result. This can be done with a lookup-style system, or it can be done more explicitly with a calculation or lookup step in a transformed saturation space.

Another issue also arises when matching electronic images with film. Film's color saturation is reduced at both high and low exposures. Although electronic cameras must lose saturation to provide the highlight "knee" function to match the "shoulder" of film's S-curve, the saturation for low exposure is inherently different. In the absence of "black stretch" in electronic cameras, the saturation of low exposure does not diminish compared to mid-level exposure. In order to obtain a forward match from film to the electronic image, the saturation at low exposure must be increased. However, given the muddy and grainy nature of low-exposure film, the forward-matching result may gain substantial color grain noise in the dark areas, as well as not being able to add sufficient saturation to obtain a dark color match. In this situation, the simplest approach is to desaturate the colors of the electronic image in the dark region, as part of the matching process. This desaturated-dark electronic matching image is then the one to which the inversion process is applied, thus achieving a match with film. The amount of this adjustment, and whether it is needed, is dependent upon the type of film being matched, as well as the exposure and developing conditions.

Conclusion

Different aspects of the invention that are considered to be novel include (without limitation) the following concepts:

- The simultaneous creation of both a "forward" electronic image match, and a "backward" film-based match
- Use of an electronic display device (including CRT and projection imaging systems such as micromirror, projection LCD, laser, *etc.*) to display an electronic image (either with or without creative adjustments) adjacent to an electronic image of a forward-corrected motion picture negative film, for use both in backward correcting the electronic image to make a film result, as well as to forward correct the film to make a matching electronic result.
- A cross color forward lookup system combined with a reverse lookup inversion.

- Use of cross-color "forward" matrix corrections, and use of the inverted matrix as the cross-color "backward" correction step.
- Use of ranges (dark to light) of cross-color matrices, both forward and backward, and their inverted counterparts.
- Use of a brightness representation curve (also called the "transfer characteristic") change prior to applying matrix based cross-color corrections, and then undoing that curve change after the matrix, as well as the inverse of this process.
- The use of alternate color spaces (such as hue-saturation-value or CIE LUV) to apply conversions to hue and saturation, and the use of their inversion for color matching.
- A color space and gamma curve view-independent matching system supporting heterogeneous electronic color primary and gamma systems as well as uncalibrated displays.
- Achieving a matching system which is not dependent on any particular display technology, and is tolerant of drift, lack of calibration, as well as multiple standards (and non-standards) for electronic display.
- Use of additional corrections to the electronic image prior to matching with film.
- Use of additional corrections to the digitized film image prior to matching with the electronic image. Such corrections to the film image can be adjusted using film-based prints, or using forward correction from film into an electronic display format.
- Use of film negative still images simultaneously with electronic photography to achieve a film-based release match.
- Use of a calibrated reference viewing environment either "on-set" or "on-location" for controlling electronic cinematography.
- Use of a simulated "S-curve" and its inversion for inverse matching film and for forward adjusting film and forward adjusting electronic images. This curve allows matching in the "toe" (dark) and "shoulder" (highlight) regions of an image.

- Use of the invention to match a heterogeneous variety of film stocks and lighting conditions, with a heterogeneous variety of electronic cameras and lighting conditions.
- Creation of a library of generic matching calibrations for film and electronic cameras under various scene content and lighting conditions, and use of this library to create film negatives for film print release from electronic cameras where no matching film negatives are available.
- Use of a calibration chart in an electronically captured scene to permit matching to that chart as imaged on various films in a generic film database, and use of the chart and the matching forward calibration together with the inversion to achieve the film transformation for film exposure of the electronic image.
- Use of a generic database as a creative tool to adjust both electronic and film originated images to appear like other desired film types or processing and printing treatments.
- Use of reduced saturation techniques to adjust electronic images for low exposure and high exposure desaturation to match film.
- Use of the invention as a method to allow users to gradually expand the range (gamut) of colors which can be presented beyond existing RGB electronic and film print systems.
- Use of multiple primary correction and adjustment systems which include cross-color corrections to simultaneously support conversions to, and matching with, color systems having differing primary colors, a differing gamut of color, and differing transfer characteristics.

Computer Implementation

Certain aspects of the invention may be implemented in hardware or software, or a combination of both. However, preferably, such aspects of the invention are implemented in computer programs executing on one or more programmable computers each comprising at least a processor, a data storage system (including volatile and non-volatile memory and/or storage elements), an input device, and an

output device. Program code is applied to input data to perform the functions described herein and generate output information. The output information is applied to one or more output devices, in known fashion.

Each such program may be implemented in any desired computer language (including machine, assembly, or high level procedural, logical, or object oriented programming languages) to communicate with a computer system. In any case, the language may be a compiled or interpreted language.

Each such computer program is preferably stored on a storage media or device (*e.g.*, ROM, CD-ROM, or magnetic or optical media) readable by a general or special purpose programmable computer system, for configuring and operating the computer when the storage media or device is read by the computer system to perform the procedures described herein. The inventive system may also be considered to be implemented as a computer-readable storage medium, configured with a computer program, where the storage medium so configured causes a computer system to operate in a specific and predefined manner to perform the functions described herein.

A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. For example, certain order-independent process steps may be performed in different sequences but provide the same results. Accordingly, other embodiments are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A method for color matching a digitized representation of a film to match the color of electronic images, and converting such electronic images for recording on film, including the steps of:
   (a) forward color matching the digitized representation to generate:
      (1) a color-matched digitized representation expressed in display units suitable for a selected display device; and
      (2) an associated set of conversion parameters; and
   (b) backward converting the electronic images using an inversion of the conversion parameters, expressed in units suitable for recording onto a selected film stock.

2. The method of claim 1, wherein the digitized representation of the film is expressed in color pixel values, and forward color matching includes applying a cross-color matrix adjustment to all color pixel values.

3. The method of claim 2, further including applying a transfer characteristic change prior to applying the cross-color matrix adjustment, and then reversing such transfer characteristic change after applying the cross-color matrix adjustment.

4. The method of claim 1, wherein the digitized representation of the film is expressed in color pixel values, and forward color matching includes:
   (a) selecting a cross-color matrix from a range of cross-color matrices, the selected cross-color matrix corresponding to the brightness of each color pixel value; and
   (b) applying the selected cross-color matrix as an adjustment to the corresponding color pixel value.

5. The method of claim 1, wherein the digitized representation of the film is expressed in color pixel values, and forward color matching includes applying a lookup table-based adjustment to all color pixel values.

6. The method of claim 1, wherein the digitized representation of the film is expressed in color pixels having logarithmic density unit values.

7. The method of claim 1, further including displaying the color-matched digitized representation on the selected display device.

8. The method of claim 7, further including color adjusting the color-matched digitized representation while such representation is being displayed.

9. The method of claim 7, further including displaying the electronic images adjacent the color-matched digitized representation on the selected display device.

10. The method of claim 9, further including color adjusting the electronic images.

11. The method of claim 9, further including adjusting color characteristics of the color-matched digitized representation while displayed on the selected display device.

12. The method of claim 1, wherein the digitized representation of the film is expressed in color pixel values, and forward color matching includes converting the pixel values to display units suitable for the selected display device by mapping.

13. The method of claim 1, wherein the color matching is performed using an RGB color space.

14. The method of claim 1, wherein the color matching is performed using a hue-saturation-value color space.

15. The method of claim 1, wherein the color matching is performed using an LUV color space.

16. The method of claim 1, wherein the color matching is performed using more than three primary colors.

17. The method of claim 1, wherein forward color matching further includes applying a simulated S-curve correction to highlight and shadow portions of the digitized representation.

18. The method of claim 1, wherein backward converting the electronic images includes applying an inverse simulated S-curve correction to highlight and shadow portions of the electronic images.

19. The method of claim 1, further including desaturating portions of the electronic images representing low exposure scene elements before backward converting such electronic images.

20. The method of claim 1, further including:
   (a) recording the electronic images;
   (b) color adjusting the electronic images within a calibrated reference viewing environment during such recording.

21. A method for color matching an electronic image for recording on film stock, including the steps of:
   (a) recording a scene using an electronic camera;
   (b) recording on still film at least one image of the scene being recorded by an electronic camera;
   (c) creating a digitized representation of at least one of the still film images;
   (d) forward color matching at least one digitized representation to generate:
      (1) a color-matched digitized representation expressed in display units suitable for a selected display device; and
      (2) an associated set of conversion parameters; and

(e) backward converting the electronic images using an inversion of the conversion parameters, expressed in units suitable for recording onto a selected film stock;

(f) recording the backward converted electronic images onto the selected film stock.

22. A method for color matching an electronic image for recording on a selected film stock, including the steps of:

(a) creating a library of forward color matched sets of conversion parameters for various types of film stock under various lighting conditions;

(b) recording one of a scene or a calibration chart as electronic images using an electronic camera under known lighting conditions;

(c) selecting a set of conversion parameters approximately corresponding to the selected film stock and the known lighting conditions of the electronic images;

(d) backward converting the electronic images using an inversion of the conversion parameters, expressed in units suitable for recording onto a selected film stock;

(e) recording the backward converted electronic images onto the selected film stock.

23. A system for color matching a digitized representation of a film to match the color of electronic images, and converting such electronic images for recording on film, including:

(a) means for forward color matching the digitized representation to generate:

(1) a color-matched digitized representation expressed in display units suitable for a selected display device; and

(2) an associated set of conversion parameters; and

(b) means for backward converting the electronic images using an inversion of the conversion parameters, expressed in units suitable for recording onto a selected film stock.

24. The system of claim 23, wherein the digitized representation of the film is expressed in color pixel values, and means for forward color matching includes means for applying a cross-color matrix adjustment to all color pixel values.

25. The system of claim 24, further including means for applying a transfer characteristic change prior to the cross-color matrix adjustment, and then reversing such transfer characteristic change after the cross-color matrix adjustment.

26. The system of claim 23, wherein the digitized representation of the film is expressed in color pixel values, and the means for forward color matching includes:

(a) means for selecting a cross-color matrix from a range of cross-color matrices, the selected cross-color matrix corresponding to the brightness of each color pixel value; and

(b) means for applying the selected cross-color matrix as an adjustment to the corresponding color pixel value.

27. The system of claim 23, wherein the digitized representation of the film is expressed in color pixel values, and the means for forward color matching includes means for applying a lookup table-based adjustment to all color pixel values.

28. The system of claim 23, wherein the digitized representation of the film is expressed in color pixels having logarithmic density unit values.

29. The system of claim 23, further including displaying the color-matched digitized representation on the selected display device.

30. The system of claim 29, further including means for color adjusting the color-matched digitized representation while such representation is being displayed.

31. The system of claim 29, further including means for displaying the electronic images adjacent the color-matched digitized representation on the selected display device.

32. The system of claim 31, further including means for color adjusting the electronic images.

33. The system of claim 31, further including means for adjusting color characteristics of the color-matched digitized representation while displayed on the selected display device.

34. The system of claim 23, wherein the digitized representation of the film is expressed in color pixel values, and the means for forward color matching includes means for converting the pixel values to display units suitable for the selected display device by mapping.

35. The system of claim 23, wherein the color matching is performed using an RGB color space.

36. The system of claim 23, wherein the color matching is performed using a hue-saturation-value color space.

37. The system of claim 23, wherein the color matching is performed using an LUV color space.

38. The system of claim 23, wherein the color matching is performed using more than three primary colors.

39. The system of claim 23, wherein the means for forward color matching further includes means for applying a simulated S-curve correction to highlight and shadow portions of the digitized representation.

40. The system of claim 23, wherein the means for backward converting the electronic images includes means for applying an inverse simulated S-curve correction to highlight and shadow portions of the electronic images.

41. The system of claim 23, further including means for desaturating portions of the electronic images representing low exposure scene elements before backward converting such electronic images.

42. The system of claim 23, further including:
   (a) means for recording the electronic images;
   (b) means for color adjusting the electronic images within a calibrated reference viewing environment during such recording.

43. A system for color matching an electronic image for recording on film stock, including:
   (a) means for recording a scene using an electronic camera;
   (b) means for recording on still film at least one image of the scene being recorded by an electronic camera;
   (c) means for creating a digitized representation of at least one of the still film images;
   (d) means for forward color matching at least one digitized representation to generate:
      (1) a color-matched digitized representation expressed in display units suitable for a selected display device; and
      (2) an associated set of conversion parameters; and
   (e) means for backward converting the electronic images using an inversion of the conversion parameters, expressed in units suitable for recording onto a selected film stock;
   (f) means for recording the backward converted electronic images onto the selected film stock.

44. A system for color matching an electronic image for recording on a selected film stock, including:
   (a) means for creating a library of forward color matched sets of conversion parameters for various types of film stock under various lighting conditions;
   (b) means for recording one of a scene or a calibration chart as electronic images using an electronic camera under known lighting conditions;
   (c) means for selecting a set of conversion parameters approximately corresponding to the selected film stock and the known lighting conditions of the electronic images;
   (d) means for backward converting the electronic images using an inversion of the conversion parameters, expressed in units suitable for recording onto a selected film stock;
   (e) means for recording the backward converted electronic images onto the selected film stock.

45. A computer program, stored on a computer-readable medium, for color matching a digitized representation of a film to match the color of electronic images, and converting such electronic images for recording on film, the computer program comprising instructions for causing a computer to:
   (a) forward color match the digitized representation to generate:
      (1) a color-matched digitized representation expressed in display units suitable for a selected display device; and
      (2) an associated set of conversion parameters; and
   (b) backward convert the electronic images using an inversion of the conversion parameters, expressed in units suitable for recording onto a selected film stock.

46. The computer program of claim 45, wherein the digitized representation of the film is expressed in color pixel values, and the instructions for forward color matching include instructions to cause the computer to apply a cross-color matrix adjustment to all color pixel values.

47. The computer program of claim 46, further including instructions to cause the computer to apply a transfer characteristic change prior to the cross-color matrix adjustment, and then to reverse such transfer characteristic change after the cross-color matrix adjustment.

48. The computer program of claim 45, wherein the digitized representation of the film is expressed in color pixel values, and the instructions for forward color matching include instructions to cause the computer to:

(a) select a cross-color matrix from a range of cross-color matrices, the selected cross-color matrix corresponding to the brightness of each color pixel value; and

(b) apply the selected cross-color matrix as an adjustment to the corresponding color pixel value.

49. The computer program of claim 45, wherein the digitized representation of the film is expressed in color pixel values, and the instructions for forward color matching include instructions to cause the computer to apply a lookup table-based adjustment to all color pixel values.

50. The computer program of claim 45, wherein the digitized representation of the film is expressed in color pixels having logarithmic density unit values.

51. The computer program of claim 45, further including instructions to cause the computer to display the color-matched digitized representation on the selected display device.

52. The computer program of claim 51, further including instructions to allow the computer to receive control signals to color adjust the color-matched digitized representation while such representation is being displayed.

53. The computer program of claim 51, further including instructions to cause the computer to display the electronic images adjacent the color-matched digitized representation on the selected display device.

54. The computer program of claim 53, further including instructions to cause the computer to color adjusting the electronic images.

55. The computer program of claim 53, further including instructions to allow the computer to receive controls signals to adjust color characteristics of the color-matched digitized representation while displayed on the selected display device.

56. The computer program of claim 45, wherein the digitized representation of the film is expressed in color pixel values, and the instructions for forward color matching include instructions to cause the computer to convert the pixel values to display units suitable for the selected display device by mapping.

57. The computer program of claim 45, wherein the color matching is performed using an RGB color space.

58. The computer program of claim 45, wherein the color matching is performed using a hue-saturation-value color space.

59. The computer program of claim 45, wherein the color matching is performed using an LUV color space.

60. The computer program of claim 45, wherein the color matching is performed using more than three primary colors.

61. The computer program of claim 45, wherein the instructions for forward color matching further include instructions to cause the computer to apply a simulated

S-curve correction to highlight and shadow portions of the digitized representation.

62. The computer program of claim 45, wherein the instructions for backward converting the electronic images include instructions to cause the computer to apply an inverse simulated S-curve correction to highlight and shadow portions of the electronic images.

63. The computer program of claim 45, further including instructions to cause the computer to desaturate portions of the electronic images representing low exposure scene elements before backward converting such electronic images.

64. A computer program, stored on a computer-readable medium, for color matching an electronic image for recording on film stock, the computer program comprising instructions for causing a computer to:

(a) record a scene using an electronic camera;

(b) record on still film at least one image of the scene being recorded by an electronic camera;

(c) create a digitized representation of at least one of the still film images;

(d) forward color match at least one digitized representation to generate:

(1) a color-matched digitized representation expressed in display units suitable for a selected display device; and

(2) an associated set of conversion parameters; and

(e) backward convert the electronic images using an inversion of the conversion parameters, expressed in units suitable for recording onto a selected film stock;

(f) record the backward converted electronic images onto the selected film stock.

65. A computer program, stored on a computer-readable medium, for color matching an electronic image for recording on a selected film stock, the computer program comprising instructions for causing a computer to:

(a) create a library of forward color matched sets of conversion parameters for various types of film stock under various lighting conditions;

(b) record one of a scene or a calibration chart as electronic images using an electronic camera under known lighting conditions;

(c) select a set of conversion parameters approximately corresponding to the selected film stock and the known lighting conditions of the electronic images;

(d) backward convert the electronic images using an inversion of the conversion parameters, expressed in units suitable for recording onto a selected film stock;

(e) record the backward converted electronic images onto the selected film stock.

66. A library of forward color matched sets of conversion parameters, produced by the steps of:

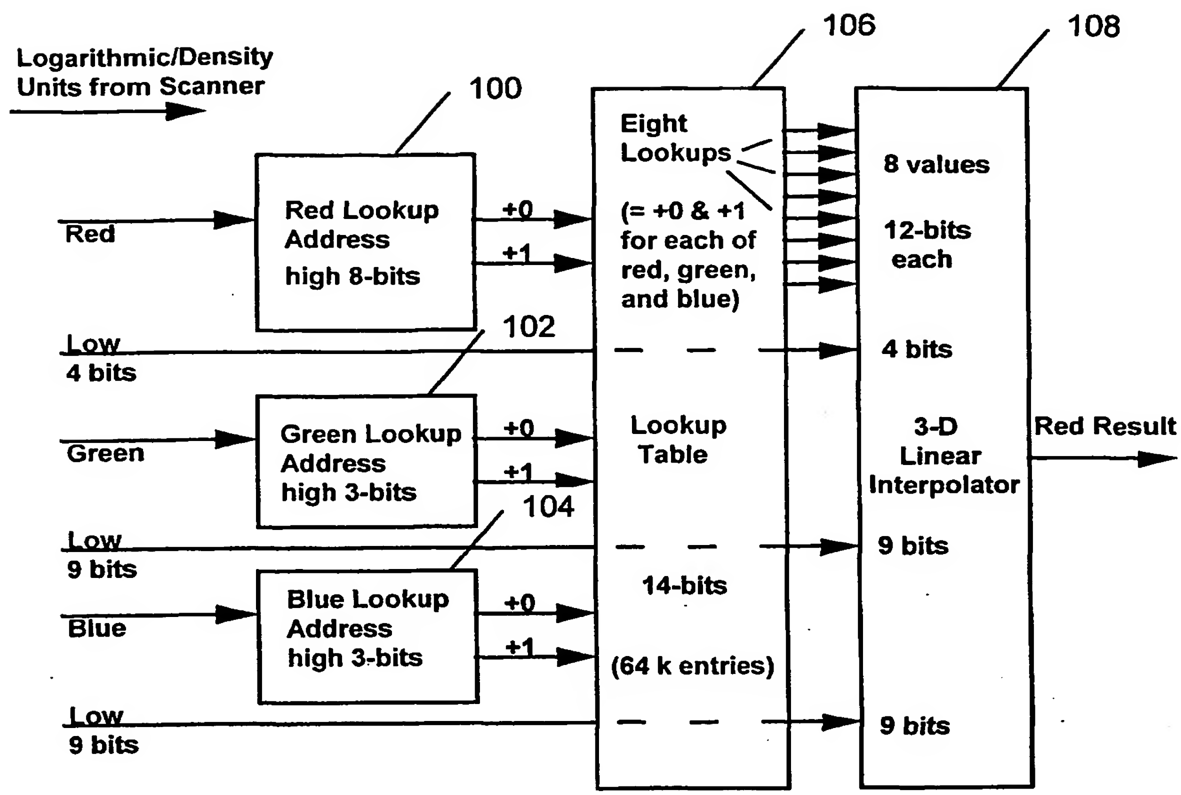
(a) recording a variety of scenes on various types of film stock under various lighting conditions;

(b) creating a digitized representation of the recorded scenes;

(c) forward color matching the digitized representations to generate:

(1) corresponding color-matched digitized representations expressed in display units suitable for a selected display device; and

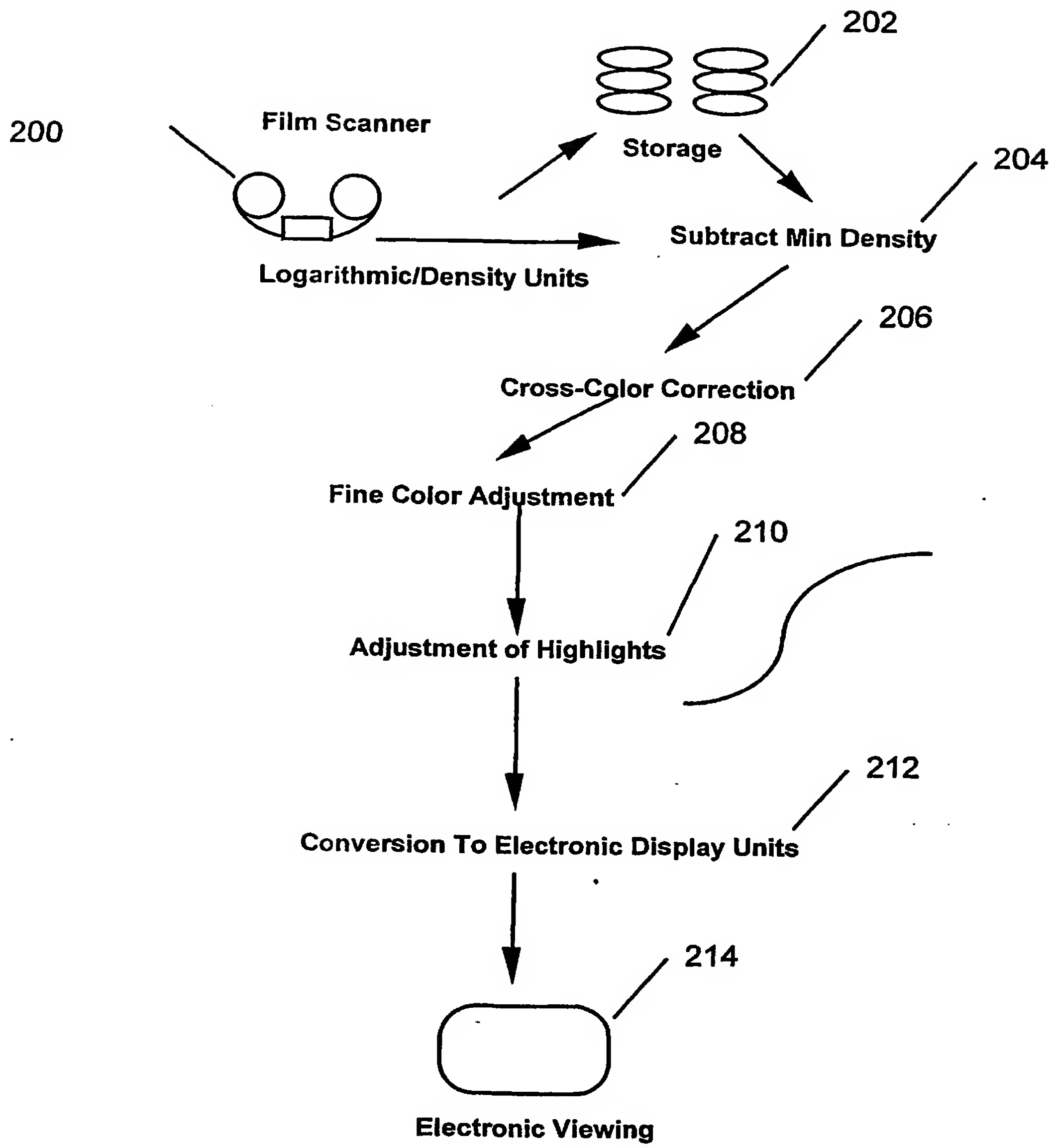
(2) an associated set of conversion parameters.



Red Cross-Color Correction System

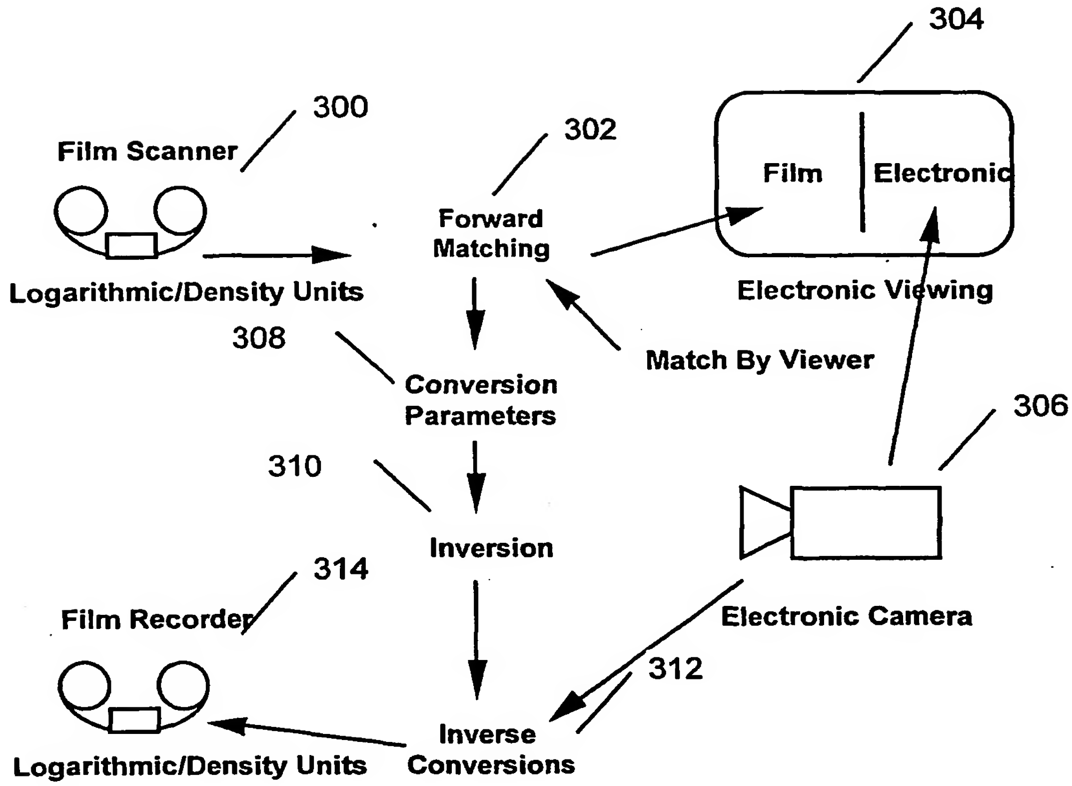
FIG. 1

(Prior Art)



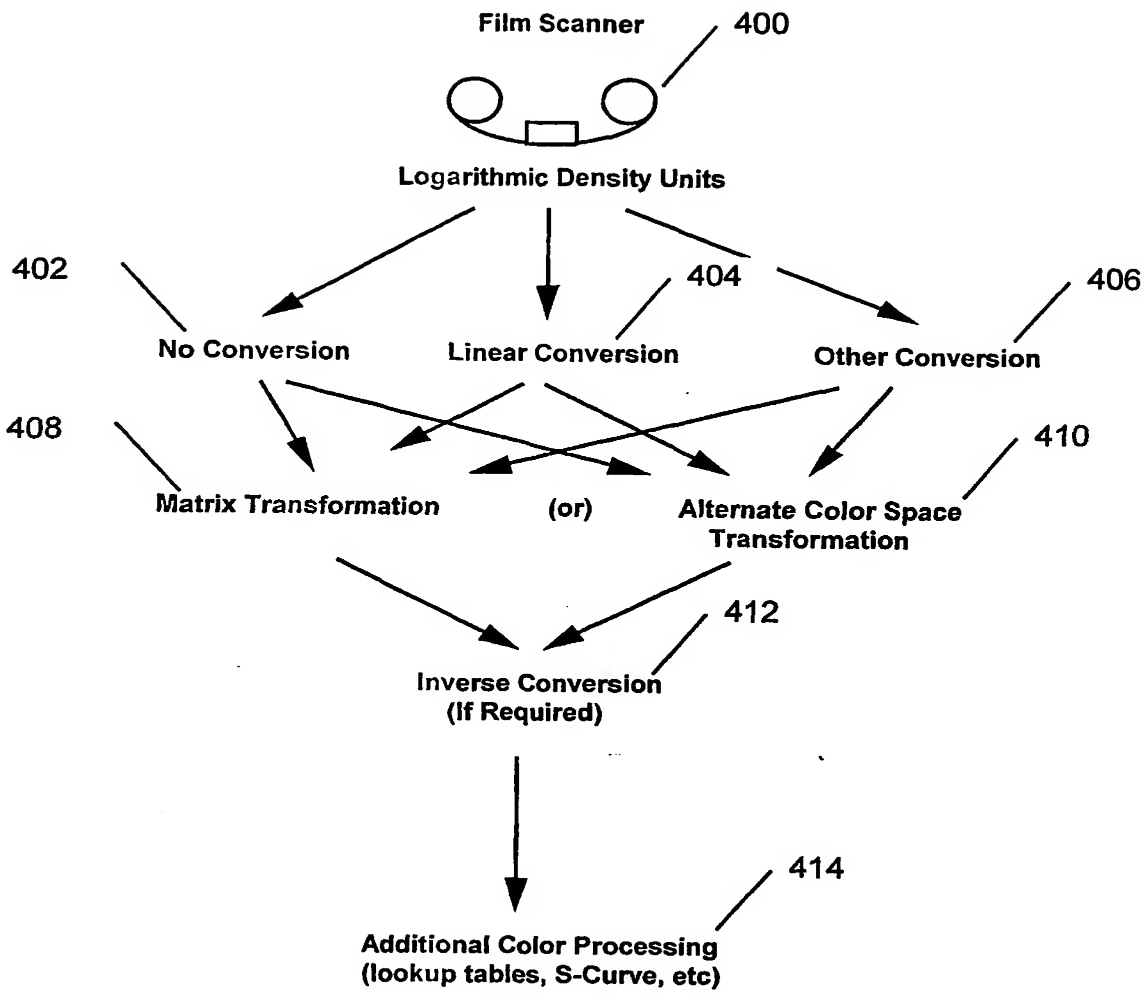
Forward Color Matching Process

FIG. 2



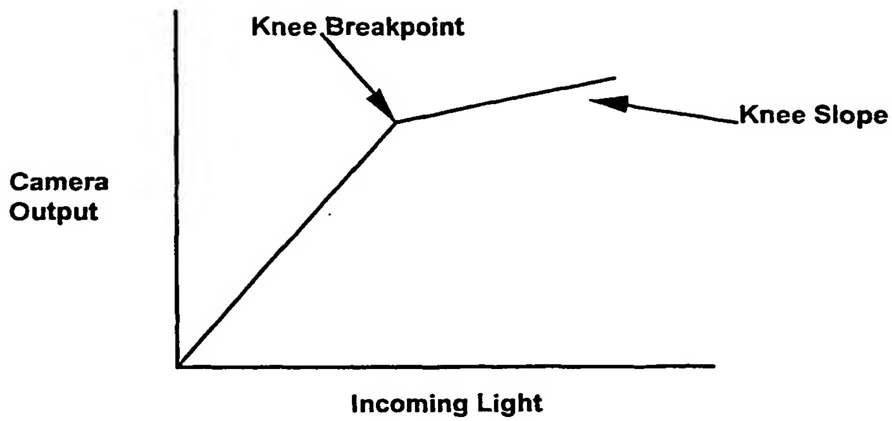
Inversion Process For Electronic Images

FIG. 3



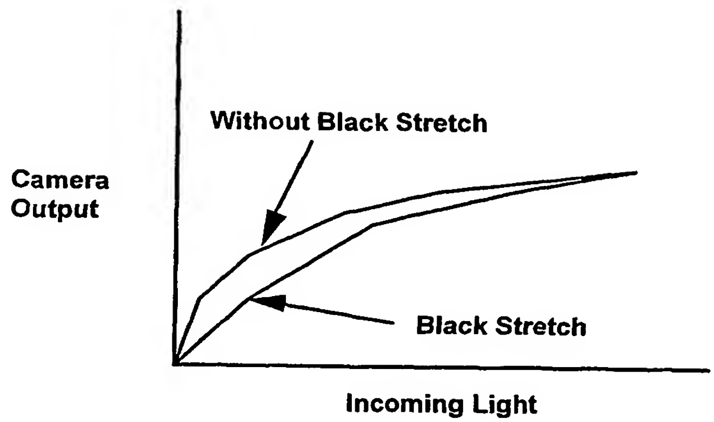
Cross-Color Conversion Spaces

FIG. 4



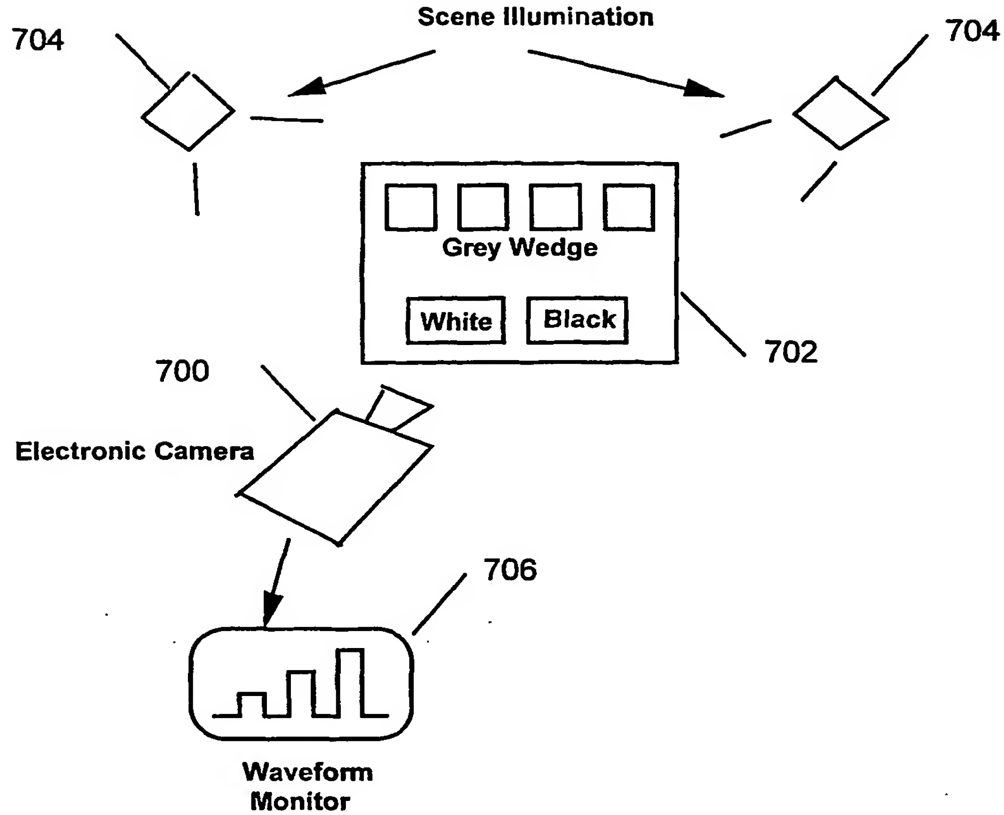
Knee Breakpoint and Slope Function

FIG. 5



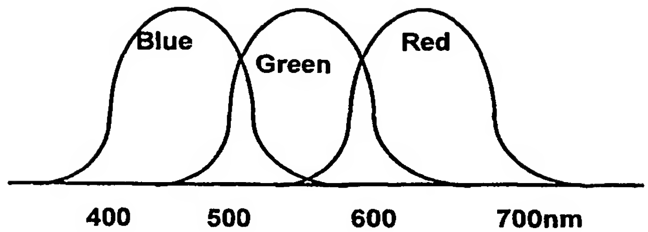
"Black Stretch" In Electronic Cameras

FIG. 6



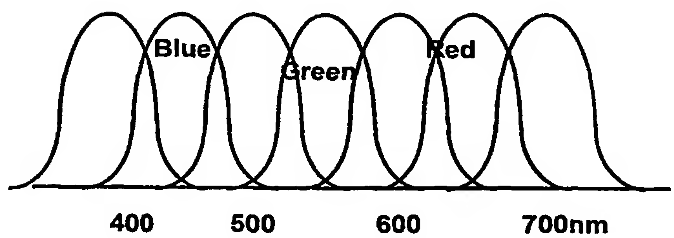
Calibration Chart Setup For Electronic Cameras

FIG. 7



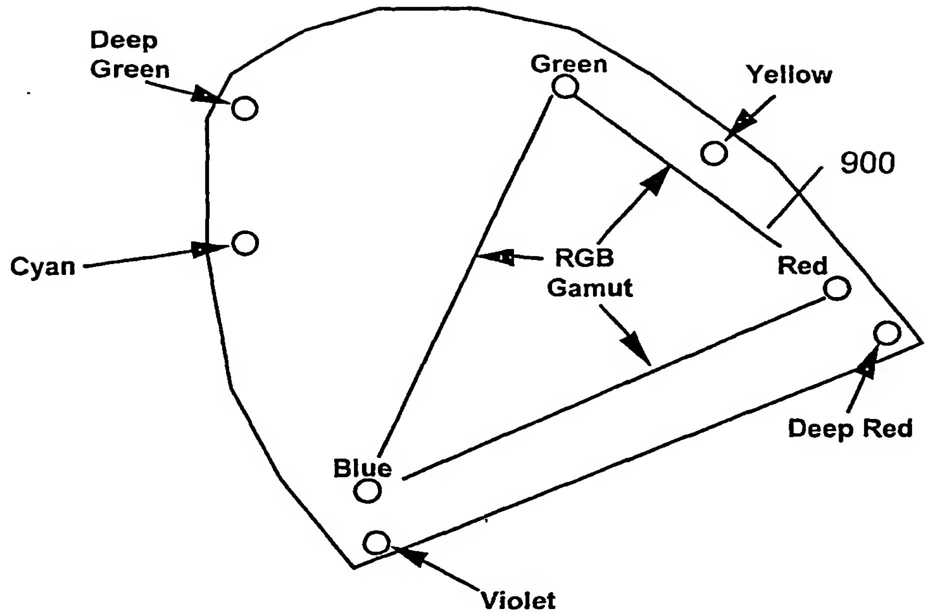
Color Sensing Curves With Three Primary Colors (RGB)

FIG. 8A



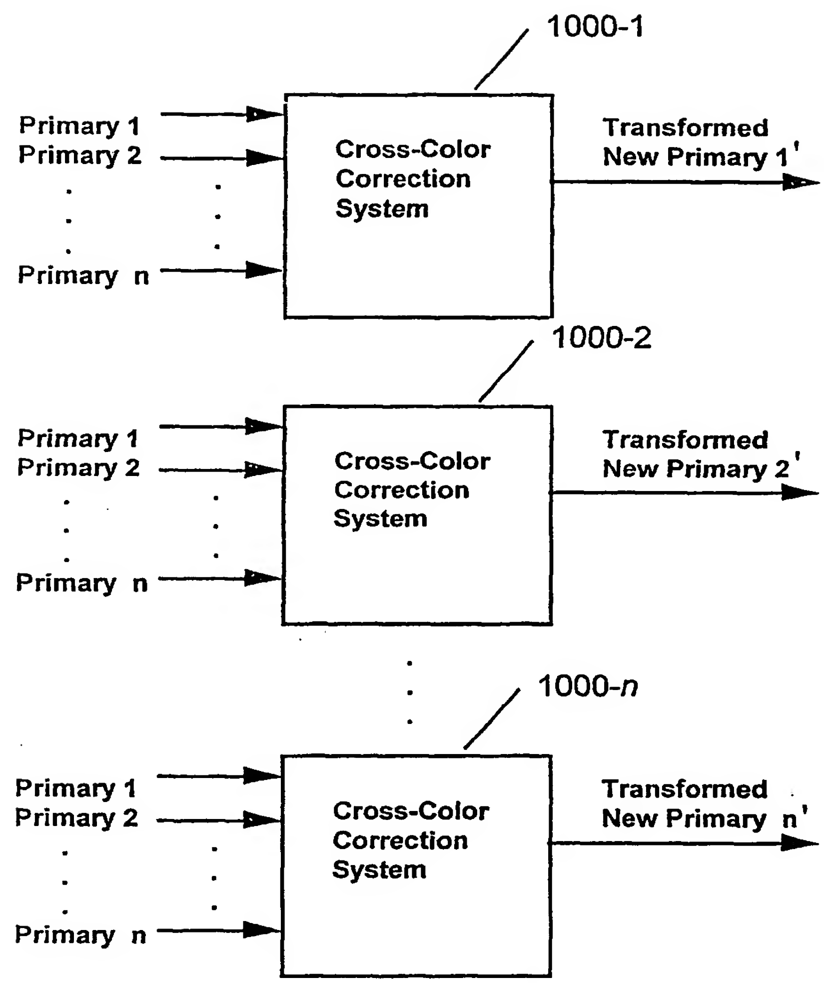
Color Sensing Curves With Additional Primary Colors

FIG. 8B



RGB Gamut Extensions Available With Additional Primaries

FIG. 9



Cross Color Correction To and From Three or More Primaries

FIG. 10